HYD 473

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

WHY CLOSE TOLERANCES ARE NECESSARY UNDER HIGH-VELOCITY FLOW

Hydraulic Laboratory Report No. Hyd-473

DIVISION OF ENGINEERING LABORATORIES

COMMISSIONER'S OFFICE
DENVER, COLORADO

October 20, 1960

CONTENTS

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

Commissioner's Office-Denver
Division of Engineering Laboratories
Hydraulic Laboratory Branch
Denver, Colorado
October 20, 1960

Laboratory Report No. Hyd-473
Compiled by: J. W. Ball
Checked by: J. W. Ball
Reviewed by: H. M. Martin
Submitted by: H. M. Martin

Subject: Why close tolerances are necessary under high-velocity flow

PURPOSE

To present information to Bureau Construction Engineers as to why close tolerances in the alinement of flow surfaces in modern engineering structures become more and more important as the flow velocities are increased.

INTRODUCTION

The material contained in this report was prepared by the author for a paper presented at the Bureau of Reclamation Construction Engineers Conference, January 25-29, 1960. The material includes data from hydraulic model studies, as well as field observations and experiences.

Typical irregularities likely to be encountered in the construction of flow surfaces in high-head engineering structures and their potential for inducing damaging cavitation are discussed with particular emphasis on the need of controlling the size of the irregularities to prevent damage.

CAVITATION POTENTIAL AND CONTROL OF FLOW SURFACES

It is reasonable to assume that many engineers are of the opinion that presently specified tolerances for flow surfaces are too rigid and, in some cases, almost impossible to meet. From strictly the construction point of view, this may appear to be true. However, from the operational point of view, close tolerances are very essential, particularly where flow velocities are high. In fact many of the present tolerances may be totally inadequate for extremely 1/ high

---

1/ Hydraulic Laboratory Report Hyd-448 "Importance of Smooth Surfaces on Flow Boundaries Downstream from Outlet Works Control Gates."

velocities. The purpose of this paper is to explain from the operational point of view why close tolerances are necessary under high-velocity flow and to show that present tolerances may not be rigid enough.

The intent of tolerances for flow surfaces is to prevent surface irregularities that will trigger flow conditions which will induce cavitation to inflict extensive damage to the structure and require costly repair and maintenance. In order to establish reasonable and safe tolerances for specifications purposes, it is necessary to know two factors: (1) types of irregularities to be encountered in constructed flow surfaces and (2) the size of each type of irregularity that can be tolerated. Much is known about the types of irregularities to be encountered, but very little is presently known of their critical sizes.

Typical types of irregularities include abrupt offsets into the flow, abrupt offsets away from the flow, abrupt curvatures and slopes away from the flow, voids, roughened surfaces, and protrusions (Figure 1). Offsets occur frequently and are one of the most troublesome of the many types of irregularities. Offsets may lie at any angle with the flow, but are usually either parallel or perpendicular to it. The perpendicular, or transverse into-the-flow offsets are usually the most objectionable (Figure 1A). Offsets away from the flow, and protruding joints (Figure 1B and Figure 1G) are also objectionable. Offsets in joints parallel to the direction of flow are not objectionable in themselves, but irregularities in the joints may be troublesome. Surfaces that curve too abruptly away from the flow (Figure 1C) induce low pressures that cause cavitation. Appreciable changes in slope, or alinement, away from the flow (Figure 1D) are also bad. Voids in the surfaces , "bug holes," or plain grooves (Figure 1E) may also be culprits. Even surface roughnesses (Figure 1F) may cause trouble. All these irregularities will cause cavitation under certain conditions.

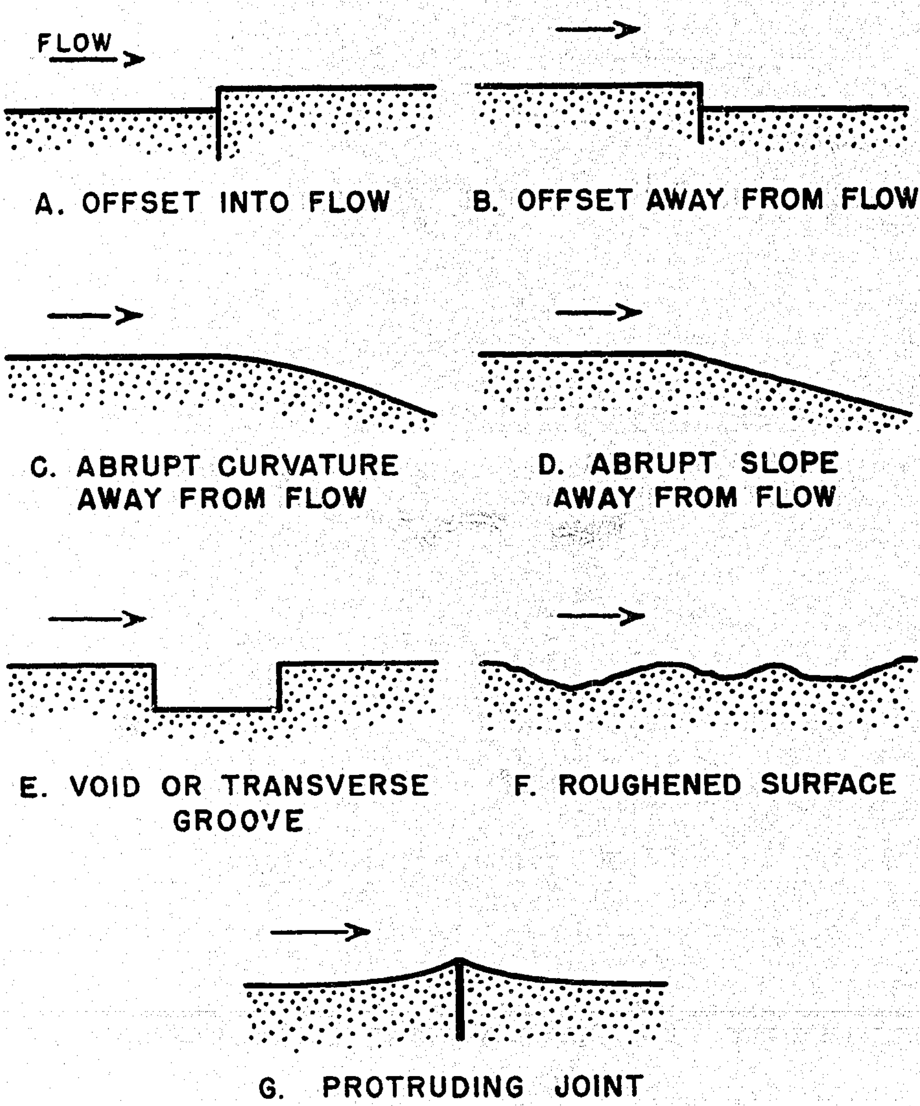


FIGURE 1. POSSIBLE CONSTRUCTION IRREGULARITIES ON FLOW SURFACES

A definition of cavitation will illustrate why these irregularities can be so objectionable. Briefly, cavitation consists of the formation, movement, and collapse of vapor cavities in a fluid. The vapor cavities, or pockets, form whenever the pressure in the fluid becomes so severely negative (subatmospheric) that vapor forms (fluid boils). This occurs in water at sea level when the pressure reaches minus 33 feet of water gage. Vapor pressure for elevation 5000 is about minus 27 feet of water gage. The vapor cavities formed are carried along by the fluid to regions of higher pressure where vapor can no longer exist. Each cavity condenses and suddenly and violently collapses. And at each point of collapse, instantaneous pressures of many thousands of pounds per square inch occur. These very high, localized, and rapidly fluctuating pressures are extremely destructive to any flow surface and produce the typical spongy appearance associated with cavitation-erosion.

The formation of low pressure zones and the action of cavitation are illustrated in Figure 2. The irregularities tend to deflect the stream from the surface. Air cannot enter the area under the jet just downstream from the irregularity, and thus a low pressure zone must form to cause the flow to stay in contact with the surface. The higher the flow velocity, the more the tendency for the jet to leave the surface and the lower the pressures become. When the velocity is such that the pressure in the zone is equal to the vapor pressure, vapor cavities form, cavitation begins (incipient cavitation), and damage may result. Once vapor pressure is reached, the pressure can go no lower, and an increase in velocity only enlarges the vapor zone, increases the rate of damage, and moves the damage farther downstream. As a rule, the larger the irregularity the lower the velocity will be to give incipient cavitation. The shape of an irregularity will also influence the velocity at which incipient cavitation will occur. This illustrates the need for more strict tolerances as flow velocities increase and explains why tolerances are varied from point to point on a structure such as the Hungry Horse Dam spillway tunnel.

The pressure within the water at the irregularity also affects the cavitation potential of the irregularity. The higher the pressure at a given irregularity, the higher the velocity must be to reduce the local pressure to vapor pressure. This means that for the same velocity a given irregularity may be critical on one structure where it is shallowly submerged, and not critical on another when it is deeply submerged or in a pressure conduit. The problem thus resolves itself into determining the critical pressure and velocity relations for each type and size of irregularity. This is extremely difficult to do in the laboratory because it is impracticable in many cases to represent conditions that are encountered in the field.

The laboratory must therefore rely on construction and operation people to obtain pertinent field data on the size and shape of irregularities

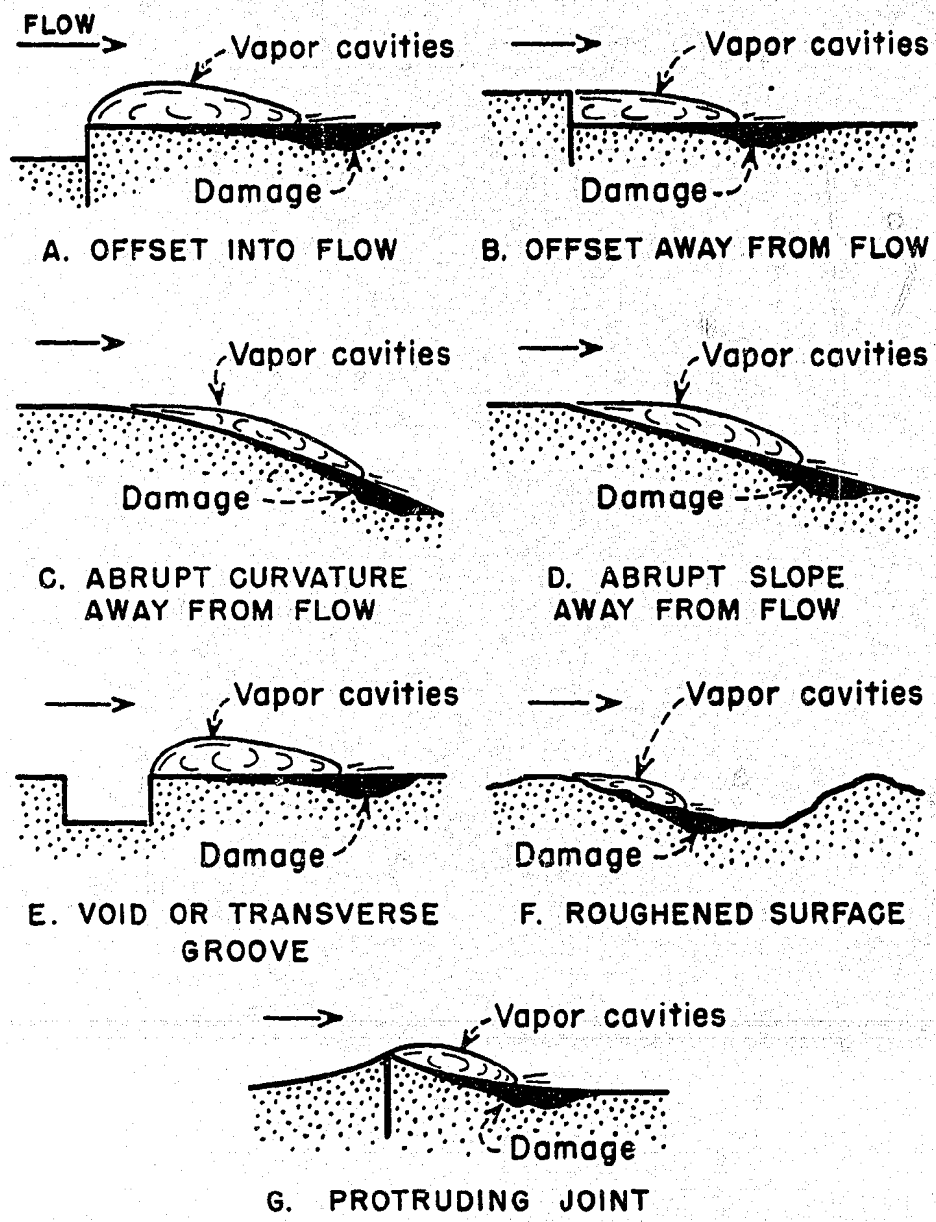


FIGURE 2. POSSIBLE OCCURRENCE OF CAVITATION AT FLOW SURFACE IRREGULARITIES

where cavitation has occurred. Much valuable information has come from the field in the past and it is hoped that this source will be even more fruitful in future years.

Several of the various types of irregularities will be discussed to illustrate their cavitation potential and to show how tolerances have been set through laboratory studies.

The first, and one of the most common, will be the offset joint. The joint may be offset either into or away from the flow (Figures 2A and 2B). The offset into the flow has the greater cavitation potential and also has the bad feature of subjecting the joint to extremely high pressures due to impact on the upstream face of the offset. Laboratory studies have established the velocity-pressure relationship for incipient cavitation for different sizes of square-edged offsets into the flow (Figure 3). With a known velocity and a known pressure, it is possible to determine the size of offset that can be tolerated. A field example of damage resulting from this type of offset is shown on Figure 4. The offset was in the concrete wall downstream from one of the outlet gates at Palisades Dam where the pressure in the water at the irregularity was nearly atmospheric. The velocity of the water was about 100 feet per second and the offset was about 1/8 inch. The chart of Figure 3 does not extend beyond velocities of 80 feet per second, but nevertheless definitely shows that cavitation will occur and that the damage should be expected. Rounding the corner will decrease the cavitation potential of the irregularity, but the influence is not known at this time.

Actually cavitation damage may reach a stable condition or may progress to reach extensive proportions, Figure 5. In cases where the surface curvature is away from the flow cavitation damage will, where the curvature is just right (Figure 5A), reach a point where recirculation occurs. This raises the pressure above the vapor pressure and cavitation ceases.

In cases where surfaces encroach upon the flowing stream (Figure 5B), the cavitation will be progressive causing extensive damage. Unfortunately most cases are of a progressive nature.

An abrupt change in alinement of the surface so that it recedes from the flow causes cavitation unless the angle is very small or is so large that the main flow definitely separates from the surface. The critical angle will depend on flow velocity, water passage shape, ambient pressure and whether or not the flow is in an open channel or a closed conduit. The higher the velocity, the smaller the angle must be to prevent cavitation pressures.

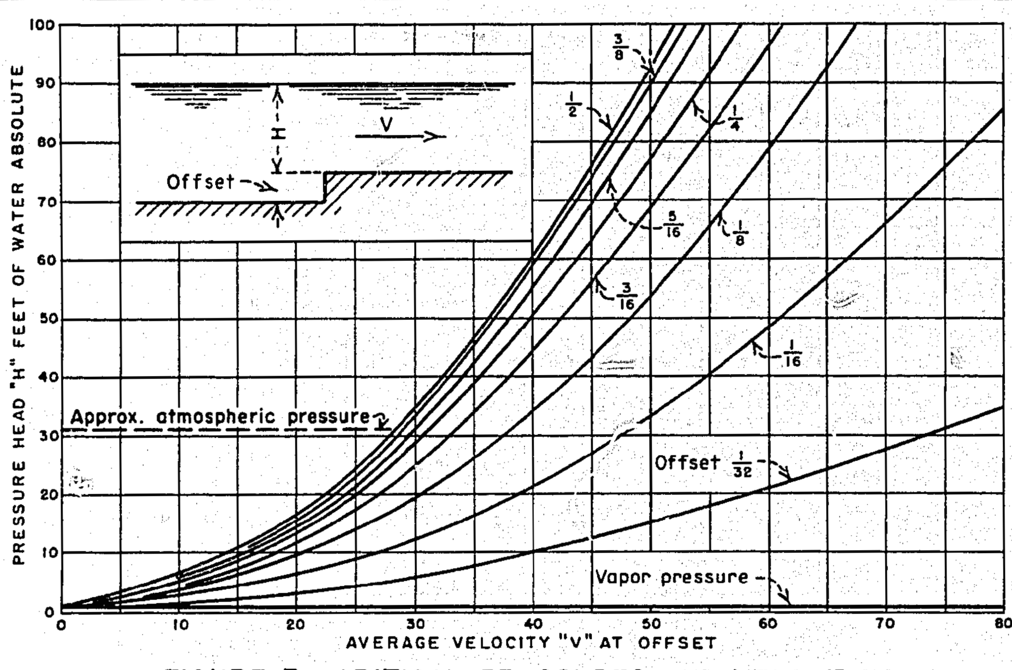


FIGURE 3. CRITICAL PRESSURES AND VELOCITIES FOR SQUARE-EDGED OFFSET INTO FLOW

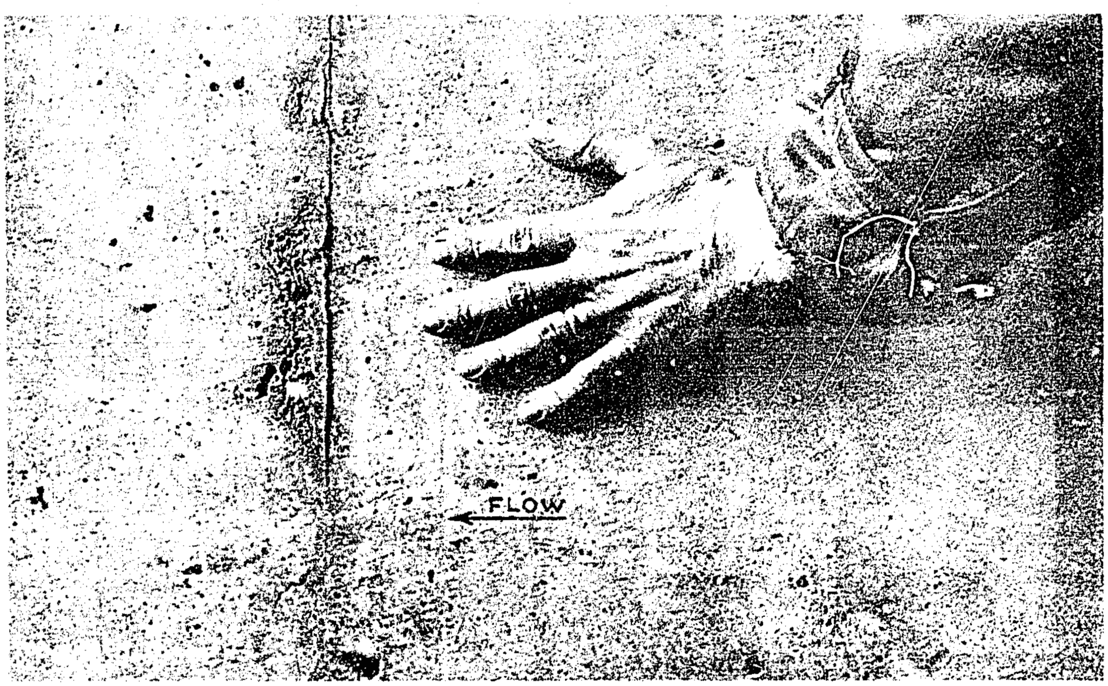
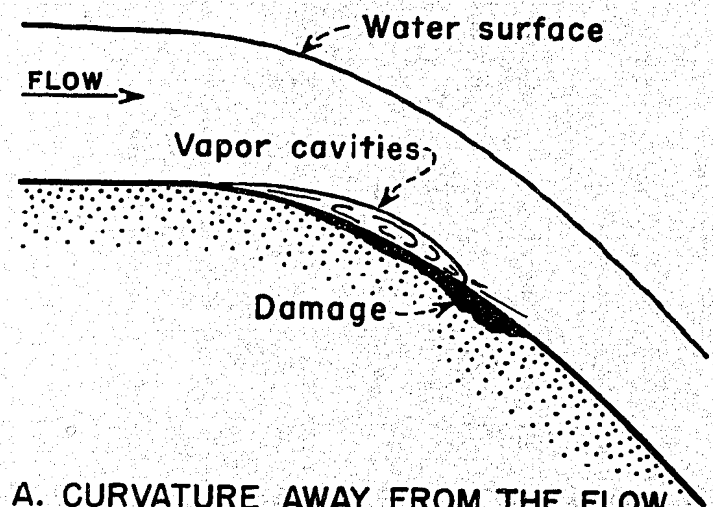
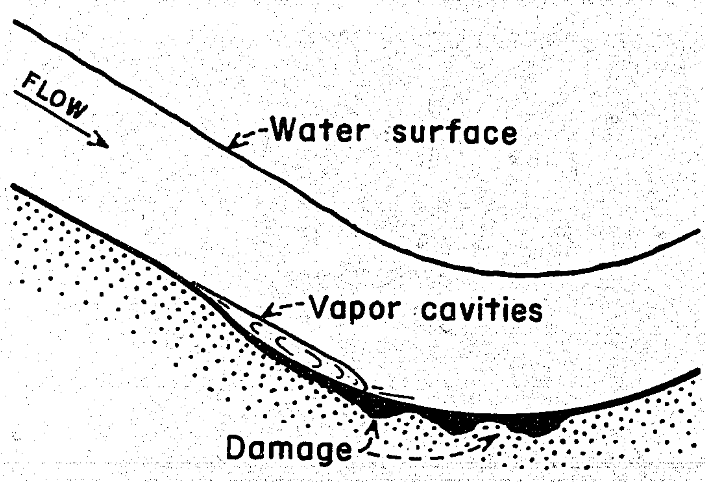


Figure 4--Cavitation-erosion downstream from 1/8 inch into-the-flow offset, atmospheric fluid pressure, and velocity of 100 feet per second--Palisades Dam Outlet Works.



A. CURVATURE AWAY FROM THE FLOW



B. CURVATURE INTO THE FLOW

FIGURE 5. CAVITATION ON CURVED SURFACES

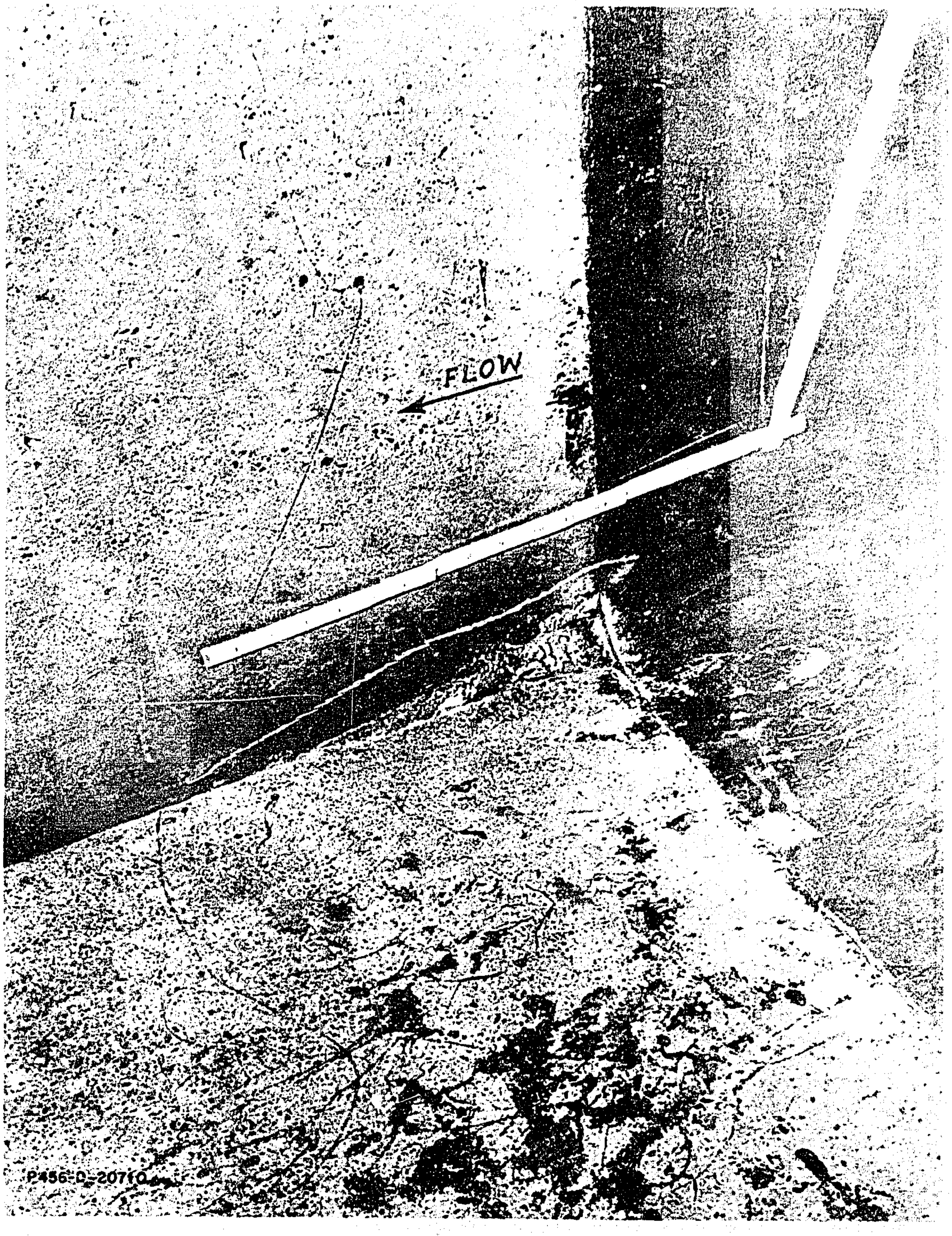


Figure 6--Slight cavitation-erosion, slope away from flow at fillet downstream from outlet gate frame--Palisades Dam.

This type of alinement change (Figure 6) was the cause of considerable damage downstream from one of the gates at Palisades Dam (Figure 7). The slope change occurred at a corner immediately downstream from the gate frame where a concrete fillet about 10 inches long sloped outward from the curve of the metal to the sharp corner in the concrete. The eroded area was several feet long, about 2 feet wide with a maximum depth of 7 inches. The irregularity was of the type shown in Figure 1D. Repair was made in such a way that the rate of slope change was sufficiently gradual to prevent pressures of vapor pressure magnitude.

Sometimes irregularities which induce cavitation are unknowingly designed into flow surfaces. This occurrence is now rare, thanks to the knowledge gained from research in recent years concerning cavitation, its nature, and causes. Also, the importance of tolerances for constructed

Figure 7--Progressive cavitation-erosion caused by slope away from flow at fillet downstream from outlet gate frame--Palisades Dam.

flow surfaces of highhead structures was realized only in recent years. An example of an irregularity designed in a surface some 22 years ago is the exit cone and trough in the upper and intermediate tiers of outlets at Grand Coulee Dam (Figure 8). The abrupt change in alinement of the surfaces, at the rate of about 1 in 16, occurs where the surface of the exit trough continues beyond the cone. This forms an irregularity similar to that shown in Figure 1D. Progressive cavitation-erosion resulted from this irregularity when the outlets recently were operated for flood control purposes (Figure 9). The damage varied widely for the 40 outlets due to various lengths of operating periods, differences in head, local bulges in concrete surfaces, offsets into and away from the flow, and various roughnesses in the concrete. Figure 10 shows the general pattern of early-stage erosion below the cone in one of the conduits.

Transverse grooves (Figure 1E), including gate slots, can be a source of much trouble. In this type of irregularity, the low pressure zone forms just downstream from the downstream corner (Figure 2E). A section through a void or "bug hole" is similar to that of a transverse groove. Damage by cavitation has been observed downstream from bug holes of about 1/2-inch diameter and larger (Figure 11). On this basis it is believed that bug holes and voids should be filled to form smooth continuous surfaces when flow velocities exceed about 50 feet per second. The hole depth and width, and the flow velocity will influence the cavitation potential of such irregularities. To date, there have been insufficient observations to establish any definite relationships. Some work on gate slots has been done in the laboratory 2/, but considerable field data covering a wide range of the variables would be extremely useful.

When repairs become necessary, it is usually not sufficient to repair only the area damaged by cavitation because this does not remove the source or cause of the trouble. Cavitation and damage will recur as soon as high-velocity flows again pass over the untouched irregularity. For permanent repair, the source, i.e., the flow surface irregularity must be removed. The cause of the damage may be near, or at a considerable distance upstream, depending on the type and extent of the irregularity and the nature of the surrounding surfaces. Under certain conditions, damage has been known to occur 20 pipe diameters distance downstream from a partially open gate valve when the partially open valve was the source of the cavitation.

Close collaboration in research, design, construction, and operation is necessary to determine and obtain the tolerances which can be safely

2/"Hydraulic Characteristics of Gate Slots," by James W. Ball, Journal of Hydraulics Division, ASCE, October 1959.

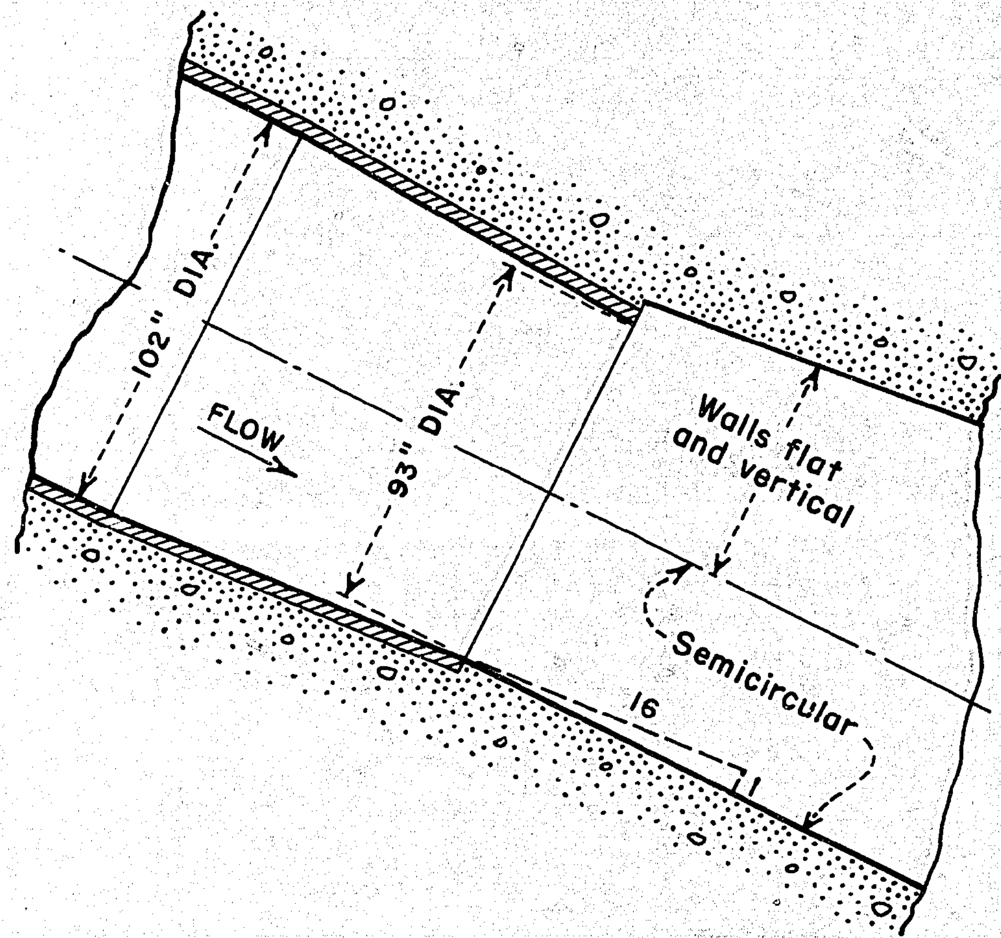


FIGURE 8. FLOW SURFACE IRREGULARITY
GRAND COULEE DAM OUTLETS

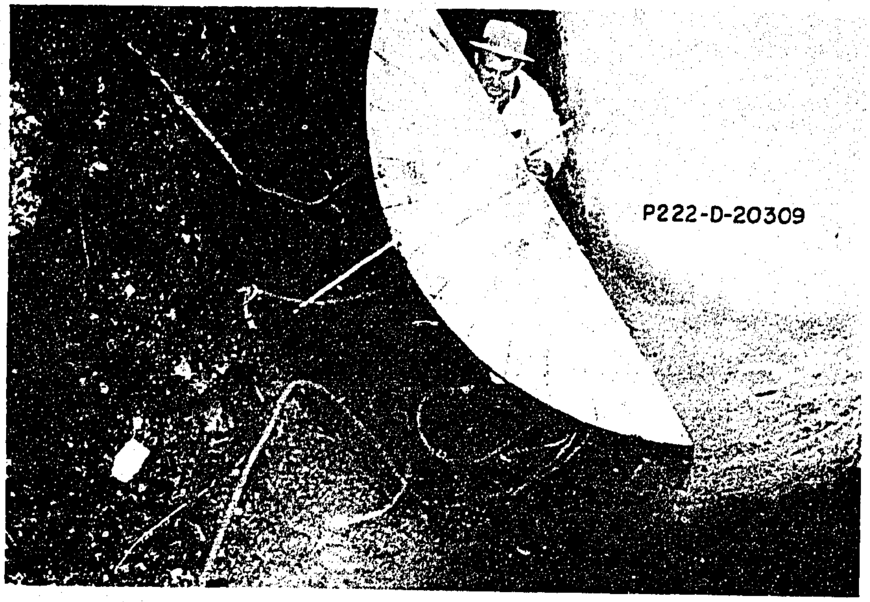


Figure 9--Severe cavitation-erosion in concrete exit trough downstream from liner cone--Grand Coulee Dam Outlet.

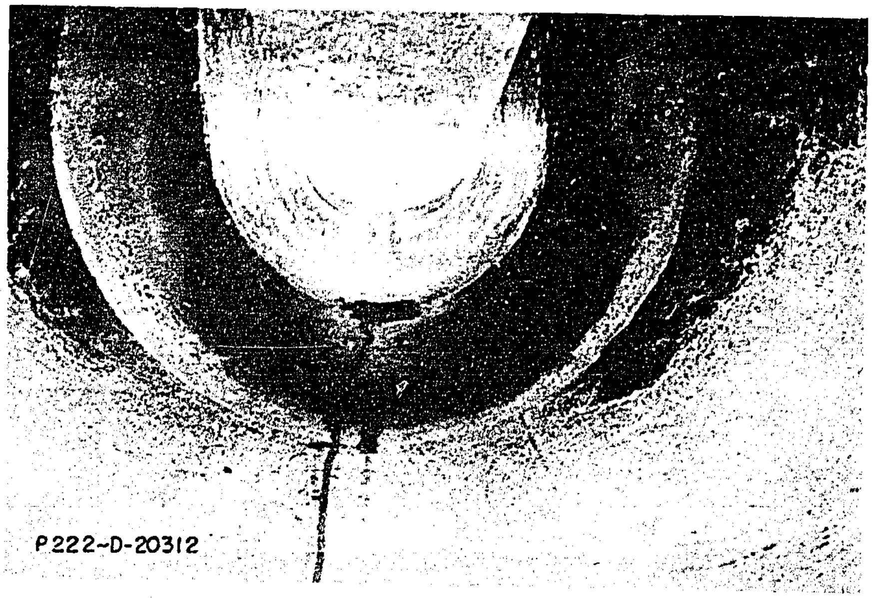


Figure 10--Typical early-stage cavitation-erosion in walls of concrete exit trough downstream from liner cone--Grand Coulee Dam Outlet.

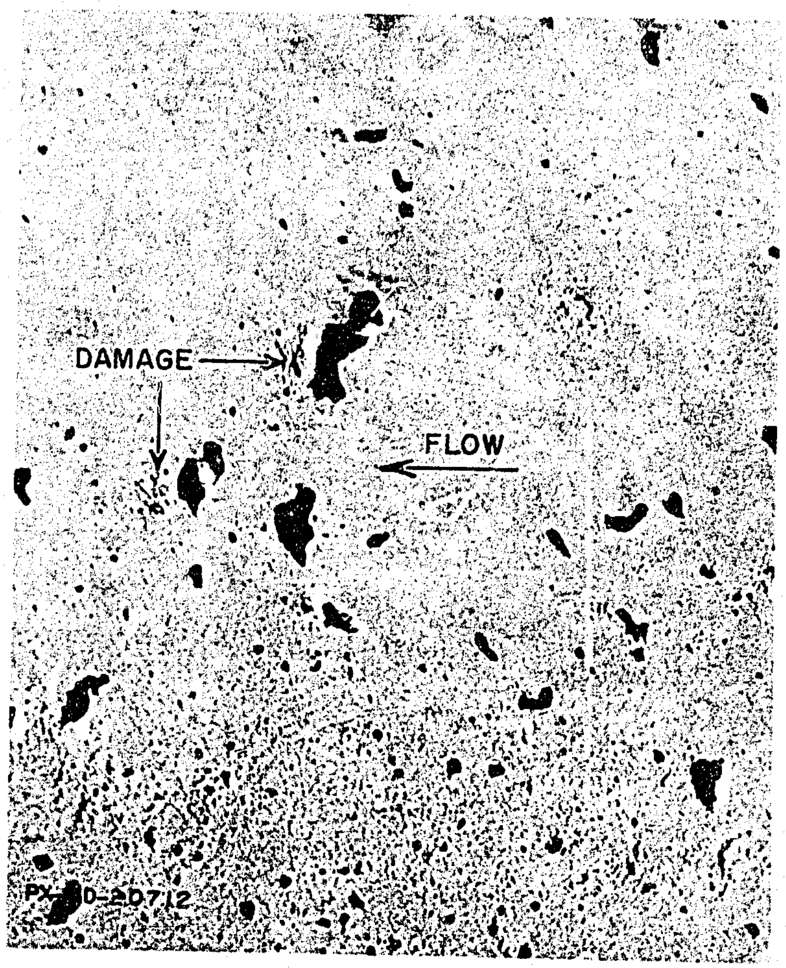


Figure 11--Cavitation-erosion downstream from "bug holes" in concrete. Velocity about 100 feet per second, pressure about atmospheric.

permitted for various irregularities under different velocities and pressures. Such collaboration is excellent in most cases, but occasionally it is not as good as it could be. For example, a field office recently, on their own, changed a design which was developed for the specific purpose of reducing the cavitation potential of the system 3/. They placed a short section of pipe between a valve and a

3/Hydraulic Laboratory Report No. 337 "Study of Gate Valves and Globe Valves as Flow Regulators for Irrigation Distribution Systems Under Heads up to about 125-feet of Water."

sudden enlargement. Unknown to them this increased the cavitation potential and will likely result in damage to the valve as well as the section of pipe that was added. The construction and maintenance costs were both increased by this change.

It is the responsibility of the research engineer to make investigations and report information which can be used by the designer to formulate sound economical up-to-date designs.

It is the responsibility of the design engineer to use all available data and resources which will enable him to design sound economical structures, and to point out areas in which research is needed.

It is the responsibility of the construction engineer to build the structure and to see that the construction is in accordance with specifications limits. Proper installation and care of test facilities during construction is most important, as is the keeping of these facilities in operable condition during construction. Important data can be lost by plugged or damaged piezometer taps and lines. Also, improper installation can produce worthless erroneous data.

It is the responsibility of the operator to note pecularities in operation, make records of test data and see that these items are available to research, design, and construction engineers.

It is only by such close collaboration that safe tolerances for high-velocity flow surfaces can be established and attained.

Summary

Many different types of irregularities will induce cavitation.

Offsets at joints, changes of alinement, voids, surface roughness, and bulges are common irregularities likely to induce damaging cavitation.

The cavitation potential of the various irregularities differs widely, depending on the size and shape of the irregularity and the pressure and velocity in the flow at the irregularity.

Present tolerances are not too rigid where high-velocity flow surfaces are concerned. The lack of knowledge concerning the cavitation potential of the various construction irregularities dictates this.

More field and laboratory studies are needed to establish the tolerances which can be safely permitted for various velocity and pressure conditions.

It is doubtful that present tolerances would be adequate for extremely high-flow velocities.

GPO 842483